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Assessment of renewable energy potential, at Aqaba in Jordan

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ABSTRACT

The present paper is aimed to assess the potential of renewable energy resources, namely wind and solar, at Aqaba city located in the southern region of Jordan. Long-term measured data of wind speed and solar irradiation at the site are utilized in this study. Skew-Normal (SN) distribution is used to describe wind speeds and irradiance levels. The main feature of SN distribution over, the well known, Weibull distribution is the possibility of applying it to a data set having zero values. The goodness-of-fit of SN-model is demonstrated graphically, via Chi-Square (CS) distribution and through Kolmogorov–Smirnov (KS) statistical test. To show the effect of turbine hub's height, wind speed characteristics and wind power potential are estimated at different heights. The recorded solar irradiation levels are separated into three clusters and SN distribution is used to fit the data of each cluster. Solar insolation characteristics; mean and most occurrence insolations, and irradiance power potential are computed and presented in this paper. The results obtained show that Aqaba has a great potential of utilizing stand-alone, grid-connected or hybrid renewable energy systems.

Contents

1. Introduction

Jordan has faced high growth rate of population and urbanization in the last decades, and consequently, the rate of energy consumption is rising rapidly. Jordan is an oil importing country and, at the same time, oil is the dominant energy sector for economic and social developments. Therefore, high amount of the Jordanian hard currency is spent to import crude oil and to refine petroleum products. Nowadays, utilization of renewable energy resources, especially wind and solar, is one of the main concerns of the Jordanian government. This is due to the expected economical and environmental benefits which will be acquired by utilizing stand-alone or hybrid renewable energy system.

In the literature, the number of publications dealing with the utilization of wind and solar energy resources in Jordan is limited. Most of the publications consider just one of renewable energy resources. Tarawneh and Sahin in [1] have applied a method called standard regional dependence function (SRDF) to compute the average wind speed in certain sites in Jordan. They concluded that the method gives acceptable results for most months in the year. In publication [2] Badran introduced a survey for the use of wind energy in Jordan to drive water pumps; even directly through mechanical means or indirectly through wind-driven electric generator. The authors in [3] applied Fuzzy sets and analytical approaches to study space-heating systems in Jordan. They showed that a space heating system based on renewable energy resource is the favorable option due to its low cost-to-benefit ratio.

Several approaches have been used to evaluate renewable energy potential. HOMER software package was implanted in [4] to study wind energy potential at four typical sites in Ethiopia. The

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SRDF method is applied in [1] to compute the average wind speed in selected sites in Jordan. Metrological approach and Weibull distribution method are implemented in [5,6] to assess the wind energy potential in Tunisia. Weibull distribution is applied in [7] to investigate wind energy resources in Sudan. The authors of the work presented in [8] have also used Weibull approach to represent the distribution of wind speed and that of solar irradiation.

In the present work, long period measured data of wind speed and solar irradiation, provided by Meteorological Department and National Energy Research Center, at Aqaba site are studied and analyzed. Skew-Normal method is implemented to describe wind speed variations and the behavior of solar irradiation. The method is examined graphically, via CS distribution and through KS statistical test. Based on 10-year (1998–2008) measured time series wind-speed, it is found that SN method is appropriate to describe wind speed distribution. Consequently, it used to evaluate wind speed characteristics and wind power potential. Before fitting the distribution of solar insolation levels, the recorded data is separated into three clusters. The authors found that Skew-Normal distribution fits well the variations in solar insolation of each cluster. Based on SN approach, solar irradiance characteristics and solar power potential are evaluated.

2. Method of data analysis

In this study, Skew-Normal statistical method is implemented to evaluate renewable energy potential in the southern region in Jordan. Azzalini has introduced this method in 1985 [9]. A comprehensive survey concerning with the method and its applications is given in [10]. The probability density function of the wind speed using the SN method could be expressed by:

$$f(V) = \frac{2}{\sigma}\phi\left(\frac{V-\mu}{\sigma}\right)\Phi\left(\alpha\frac{V-\mu}{\sigma}\right) \tag{1}$$

where $\phi(x)$ and $\Phi(x)$ are, respectively, the probability density function and cumulative distribution function of the standard normal distribution. The symbol α represents the skewness parameter. $\sigma > 0$, $-\infty < \mu,\ \alpha,\ v < \infty$. Using SN-method, wind speed characteristics can be given by:

$$V_M = \mu + \sqrt{\frac{2}{\pi}}\frac{\alpha\sigma}{\sqrt{1+\alpha^2}} \tag{2}$$

$$V_F = \text{argument of max}\, v\, f(v) \tag{3}$$

$$V_E = \text{argument of max}\, v^3 f(v) \tag{4}$$

Since V_F and V_E have no closed forms, numerical solutions are required to find them. In the present study, *NMAXIMIZE* Mathematica built-in function is used to estimate these parameters. Wind speed is recorded near ground surface; at 10 m height. Therefore, an appropriate adjustment for the wind speed at the desired turbine hub's height has to be applied. In this work, wind speed at 40 m and 60 m heights are estimated using the following equation [11]:

$$V = \frac{\ln(h/z)}{\ln(h_r/z)}V_r \tag{5}$$

where V is the wind speed at projected height h, V_r is wind speed at reference height h_r and z is roughness height, which is affected by the site's topography. The z value for Aqaba site is 0.2 [11].

The available wind power density; wind power per unit area, could be given by [5,7,12]:

$$P_W = 0.5\alpha\rho C_P\sum_{i=1}^{n}[V_i^3 f(v_i)] \tag{6}$$

where $\alpha = 0.593$ is the maximum efficiency of Betz limit, ρ is the air density depends on temperature and atmospheric pressure, C_p is the power coefficient depends on wind turbine used and V_i^3 is the cubic of the ith wind speed data. In present study, ρ is 1.77 kg/m^3 [12] and C_p is assumed 1. The last equation could be rewritten as:

$$P_W = 0.53\sum_{i=1}^{n}[V_i^3 f(V_i)] \tag{7}$$

The available wind energy density in the period T can be given by:

$$E_W = \int_T P_W\, dt \tag{8}$$

The mean solar insolation level is obtained using Eq. (9). The most frequent irradiance is evaluated using Eq. (10) and *NMAXIMIZE* function.

$$\lambda_M = \mu + \sqrt{\frac{2}{\pi}}\frac{\alpha\sigma}{\sqrt{1+\alpha^2}} \tag{9}$$

$$\lambda_F = \text{argument of max}\, \lambda\, f(\lambda) \tag{10}$$

The output electrical power of a *PV*-generator depends on the random variations of the environmental parameters (irradiance and ambient temperature) and non-linear *I*–*V* characteristic of the solar cell module constituting the generator.

The average output power from the PV-generator can be expressed by [8]:

$$P_{pv,av} = \int P(\lambda)\, f(\lambda)\, d\lambda \tag{11}$$

where $f(\lambda)$ is probability density function; here it is SN-PDF, and $P(\lambda)$ is the electrical power obtained by the PV-generator. Mathematical derivations concerning with PV model are presented in Appendix A and the parameters of the selected PV module are given in Appendix B.

3. Results and discussion

The results and findings obtained are based on daily average of 10 years measured wind speeds data and daily average of five years measured solar insolation levels data. Profiles of wind speeds and irradiance levels are shown in Fig. 1. The main objectives of the present work are to estimate wind speed characteristics and wind power potential at different heights. In addition, the study is aimed to compute statistical measures, associated with solar insolations, and solar power potential. Skew-Normal statistical method is implemented to achieve these goals. The goodness of fit of SN models is examined graphically and through statistical tests: Chi-Square (CS) and Kolmogorov–Smirnov (KS) tests.

Fig. 2A presents histogram and probability density functions versus average daily wind speed data. A plot of the empirical and fitted distributions for the average daily wind speed data is shown in Fig. 2B. The dashed lines in these figures represent SN-distribution and solid lines represent meteorological data. Table 1 shows test statistics and the parameters of SN distribution. The value between brackets for KS-distribution represents the *P*-value; the smaller the *P*-value the worse model in fitting wind speed data. Based on the graphical demonstration in Fig. 2 and the results of the two statistical tests in Table 1, the authors can strongly recommend the fitted SN distribution as an appropriate model for daily average wind speeds data. Since the fitted SN-distribution passes both graphical and goodness of fit tests, SN method is used to estimate wind speed characteristics, wind power per unit area and annual wind energy per unit area. Table 2 provides information about the effect of height

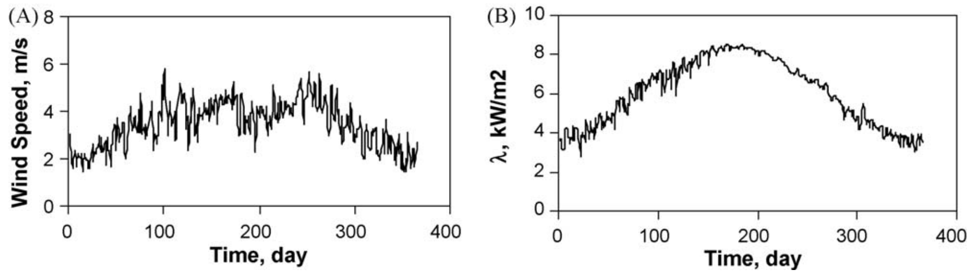

Fig. 1. (A) Daily average wind speeds. (B) Daily average solar insolation levels.

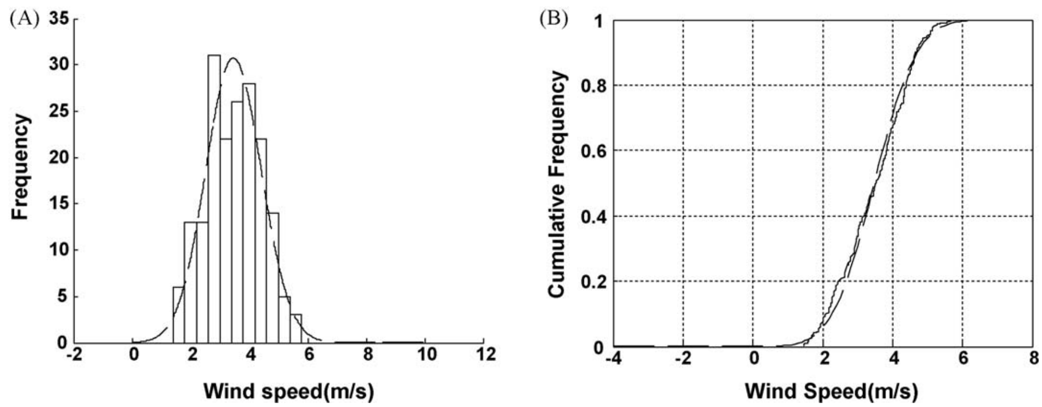

Fig. 2. (A) Histogram and probability density functions versus average daily wind speed data. (B) Plot of the empirical and fitted distributions for the average daily wind speed data

on wind speed characteristics. Maximum wind power and annual wind energy production are presented in Table 3. The mean speed and most energetic speed at height of 60 m, compared with their estimated values at height of 10 m, acquire profits of approximately 48.6% and 41%, respectively. The obtained wind energy is greatly enhanced when the height is increased from 10 m to 40 m. The increase in wind energy is approximately 148%.

Table 1
Statistical examinations applied to Skew-Normal.

	KS-distribution C.S.-test	Method's parameters	
Skew-Normal method	0.0607 (0.7461)	0.0809	$\mu = 3.04089$ $\sigma = 1.04857$ $\alpha = 0.616379$

Irradiance levels data, shown in Fig. 1B, are separated into three groups and SN-distribution is examined to fit each group using graphical demonstration and goodness of fit tests. Fig. 3A shows histogram and probability density functions versus average daily irradiance levels for cluster A. The empirical and fitted distributions for the average daily solar insolations are demonstrated in Fig. 3B. The same sequences of graphical demonstration for clusters B and C is shown in Figs. 4 and 5. In each of the previous figures, meteorological data and SN-method results are represented by solid line and dashed line, respectively.

It can be noticed that SN method is a highly convincing choice to describe the three separated groups of the long-term measured solar irradiation levels. Solar irradiance characteristics obtained by the metrological and Skew-Normal methods are presented in Table 4. The obtained λ_M and λ_F results using SN-method are closer to their corresponding metrological results. It can be noticed that

Table 2
Estimated wind speed characteristics at different heights.

Parameter (m/s)	Skew-Normal			Meteorological		
	$H = 10$ m	$H = 40$ m	$H = 60$ m	$H = 10$ m	$H = 40$ m	$H = 60$ m
V_M	3.4799	4.7061	5.2293	3.4744	4.7056	5.1620
V_E	4.1255	5.5670	6.1549	4.2585	5.4508	6.0145
V_F	3.4597	4.7023	5.2172	2.9445	3.9608	5.1601

Table 3
Estimated wind power density and wind energy density at different heights.

Parameter	Skew-Normal			Meteorological		
	$H = 10$ m	$H = 40$ m	$H = 60$ m	$H = 10$ m	$H = 40$ m	$H = 60$ m
P_W (W/m^2)	34.7400	86.308	113.932	37.301	90.066	120.957
E_W (kWh/m^2 year)	304.323	756.060	998.046	326.753	788.977	1059.582

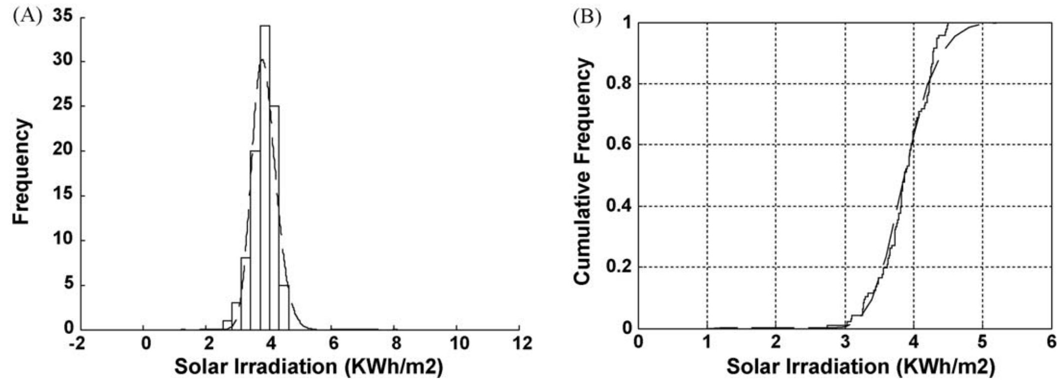

Fig. 3. (A) Histogram and PDFs versus average daily irradiance of cluster A. (B) A plot of the empirical and fitted distributions for cluster A.

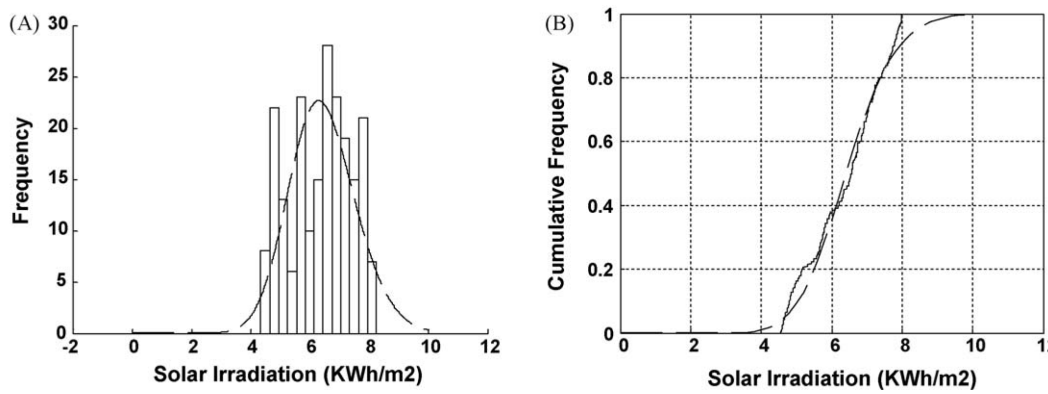

Fig. 4. (A) Histogram and PDFs versus average daily irradiance of cluster B. (B) A plot of the empirical and fitted distributions for cluster B.

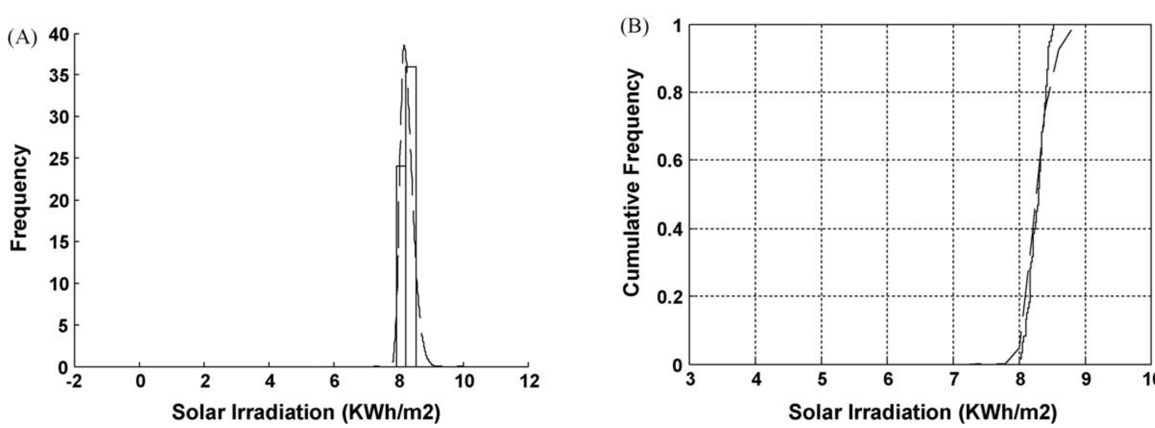

Fig. 5. (A) Histogram and PDFs versus average daily irradiance of cluster C. (B) A plot of the empirical and fitted distributions for cluster C.

Table 4
Irradiance characteristics.

Method parameter	Meteorological			Skew-Normal		
	Cluster A	Cluster B	Cluster C	Cluster A	Cluster B	Cluster C
λ_M (kW/m^2)	3.867	6.383	8.282	3.890	6.456	8.284
λ_F (kW/m^2)	3.543	6.819	8.454	3.815	6.301	8.163
Size	96	210	60	96	210	60
μ				3.52567	5.50285	8.05012
σ				0.53366	1.47804	0.30823
α				1.64516	1.37343	3.06606
$P_{\text{pv.av}}$ (W)	471.693	845.917	1134.45	476.042	845.933	1128.33
$E_{\text{pv.av}}$ (kWh/m^2 year)	452.825	1776.419	580.671	457	1776.459	677

cluster C has the highest average solar irradiation level. Moreover, the most frequent irradiance λ_F value is the greatest during this group of data. This cluster represents May–August period of the year.

4. Conclusion

The potential of renewable energy resources; wind and solar, at Aqaba in southern part of Jordan has been evaluated in the present work. Skew-Normal statistical method is utilized to evaluate wind speed characteristics and wind power potential at different heights. The long-term measured solar insolations are divided into three statistical modes and SN-method is used to fit the data of each group. Irradiance characteristics and solar power potential are presented in this publication. Based on the findings presented in this publication, it could be concluded that Aqaba has a strong potential to implement off-grid, grid-connected or integrated wind/PV energy system.

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The authors express their deep thanks to Mr. Mohammad Alawneh in National Energy Research Center for his time and effort in providing them with solar irradiation data which is used in the present study.

Appendix A. PV model

The terminal I–V characteristic of a PV-generator consists of N_S series cells (or modules) and N_P parallel strings could be represented by:

$$V = A_{VT} \ln\left(\frac{I_{PH} - I + I_{Sat}}{I_{Sat}}\right) - IR_S \tag{I1}$$

where

$$A_{VT} = \left(\frac{AKT_R}{q}\right)\left(\frac{T_A}{T_R}\right), \quad I_{PH} = N_P[1 + a(T_A - T_R)]I_1 \frac{\lambda}{100}$$

$$R_S = \frac{N_S}{N_P}R_C, \quad I_{Sat} = I_0\left(\frac{T_A}{T_R}\right)^3 \exp\left[-b\left(\frac{1}{T_A} - \frac{1}{T_R}\right)\right]$$

The parameters: A_{VT}, R_S, I_{PH} and $I_R A, K, q, T_R, R_C, I_0, I_1$, are the thermal voltage constant, the total series resistance, the total photo-current and total saturation current, completion factor, Boltzman constant, electron charge, reference temperature (25 °C), cell resistance, reference saturation current, reference cell' photo-current, respectively. The coefficients a and b depend on the solar cell material and the manufacturing process. The output power of the PV-generator is given by:

$$P = IV = IA_{VT}\ln\left(\frac{I_{PH} - I + I_{Sat}}{I_{Sat}}\right) - I^2 R_S \tag{I2}$$

The maximum power can be obtained by differentiating the above equation with respect to I then equating to zero:

$$0 = -I_{PH} + I_M + I_{Sat}\left[\exp\left(\frac{2I_M R_S}{A_{VT}} + \frac{I_M}{I_{PH} - I_M + I_{Sat}}\right) - 1\right] \tag{I3}$$

where I_M represents the current I at maximum power point. The last equation could be solved numerically to find I_M. The voltage at maximum power point, V_M, could be obtained by substituting I_M in Eq. (I1). The maximum power is then obtained by multiplying V_M by I_M.

Appendix B. PV parameters

The parameters of the PV-generator considered in the current study, at a temperature of 25 °C and solar irradiation of 1000 W/m^2 (1 Sun), are:

A_{VT} = 23.697 V, R_S = 0.9 Ω, I_{PH} = 13.615, I_R = 0.0081 A, I_M = 11.28 A, V_M = 124.2 V, P_M = 1400.8 W.

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